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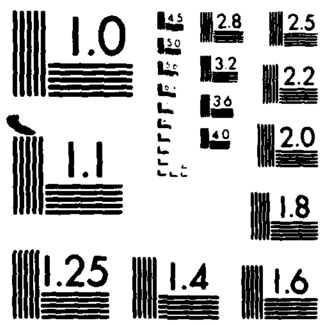

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Emergency egress exposes aircrewmembers to abrupt accelerative and windblast forces. For the time period January 1967 to December 1977, 399 ejections were made from the F-4 aircraft. Forty-three aircrewmen sustained 95 long bone and joint injuries. Of this number, 39 were identified as uppper and 21 as lower extremity injuries. The purpose of this paper is twofold. First, is to identify the region, nature, and severity of long bone and joint injuries resulting from aircraft ejection. The second is to review known biomedical data on bone and joint strength.

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INTRODUCTION

Emergency egress exposes aircrewmembers to abrupt accelerative and windblast forces. For the time period January 1967 to December 1977, 399 ejections were made from the F-4 aircraft. Forty-three aircrewmen sustained 95 long bone and joint injuries. Of this number, 39 were identified as upper and 21 as lower extremity injuries. The purpose of this paper is twofold. First, is to identify the region, nature, and severity of long bone and joint injuries resulting trom aircraft ejection. The second is to review known biomedical data on bone and joint strength.

OPERATIONAL DATA

The frequency and distribution of the 39 upper extremity and 21 lower extremity injuries are presented in Figure 1. Discussion of those specific injury locations follows:

KNEE

The knee joint is a synovial joint formed by the articulation of the distal femur, proximal tibia, and the posterior aspect of the patella. This joint is the most massive articulation in the body; and its exposed position makes it vulnerable to many types of injuries, involving both bony and soft tissue components. The stability of the knee joint is dependent upon the ligamentous apparatus and the muscles that motorize the joint.

- Type: Ligaments—medial collateral tear-dislocation
  Menisci—medial meniscus tear

- Frequency: 44%

- Mechanism: The function of the ligament is to prevent abnormal motion of the joint in a particular direction. If the stress applied to a joint is of sufficient intensity to produce abnormal motion, the protecting ligament will be injured. For injury the foot is forced in external rotation and an abducting force occurs at the outer aspect of the knee, forcing the thigh to rotate inward and the calf to rotate outward.

- Etiology: Windblast causes the foot to be forced back and out, after the extremity becomes malpositioned beyond the geometry of the seat. An abducting force at the outer aspect of the knee forces rotation beyond the range of motion of the joint. Forced external rotation, accompanied by valgus movement of the foot and calf cause injury.

The common fractures about the knee are the supracondylar fractures and intercondylar on the femur (discussed under long bones).

ANKLE

This synovial joint is of the hinge variety; however its axis of rotation is not fixed but changes between extremes of plantar flexion and dorsiflexion.

- Type: Malleoli—Medial malleolus fracture
  Dislocation—lateral subtalar dislocation

- Frequency: 9%

- Mechanism: The bony configuration of the ankle joint provides inherent stability. The joint is comprised of the distal end of the tibia and the medial malleolus on one side, and the distal end of the fibula and the medial malleous on the other. The malleoli are of unequal length and shape. When the foot is planta-flexed the narrow posterior portion of the talus advances forward into the mortise. This position produces lateral instability. In

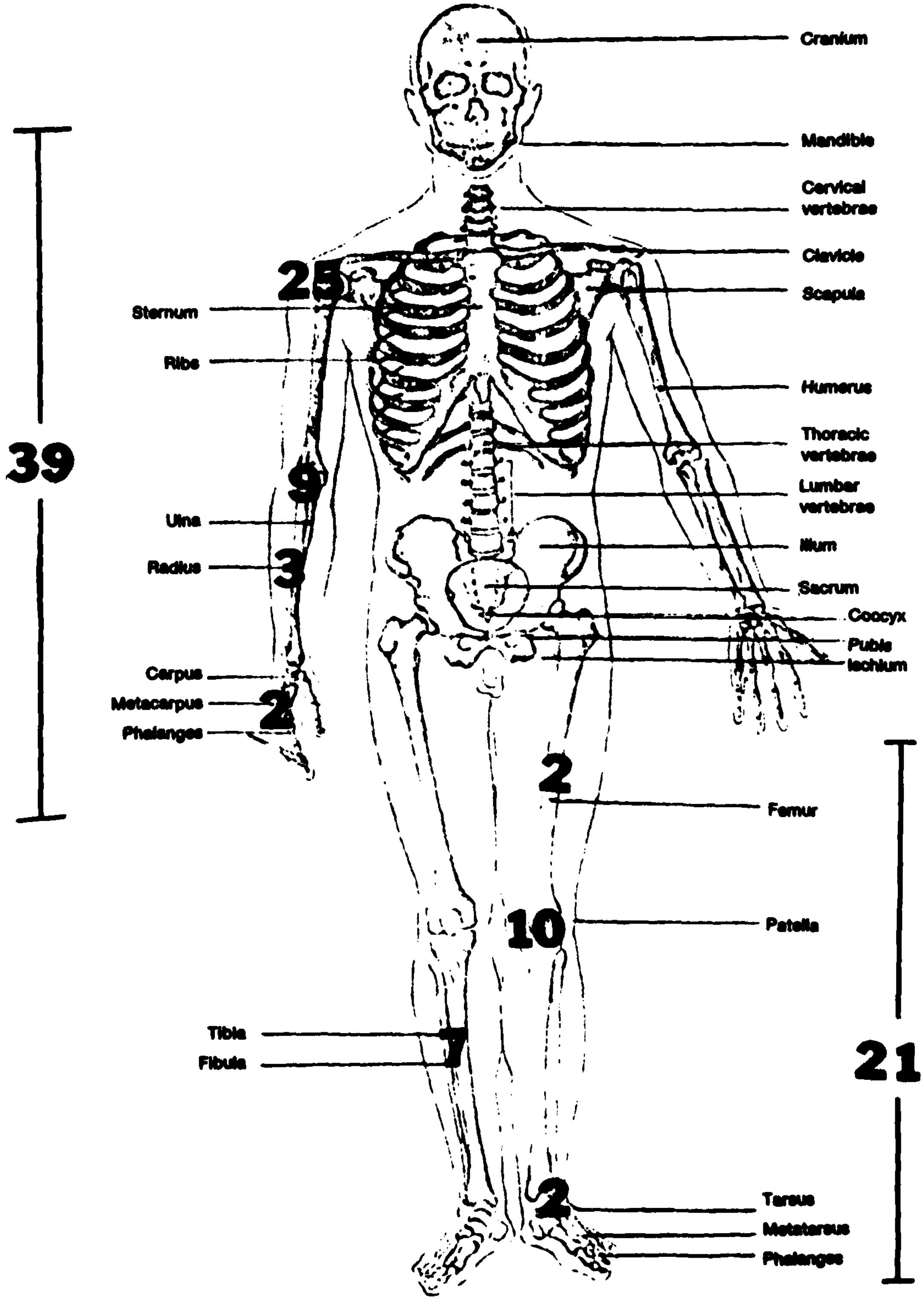

FIGURE 1. Number and Location of Upper and Lower Extremity Injuries.

general, injuries result from sideward stresses forcing the ankle beyond normal arcs of motion. As the foot inverts in relation to the leg, the lateral collateral ligament is stretched and tears if the force continues. Further continuation of the force jams the talus against the medial malleolus. The tip of the malleolus engages the body of the talus, providing a fulcrum which causes the talus to rotate over the malleolus. The resulting rupture of the lateral ligament and fracture of the medial malleolus predisposes dislocation, laterally.

● Etiology: Rotation and inversion of the foot with intense lateral forces. This condition is created when the foot is caught in the windstream beyond the seat protection and the foot/calf is thrust backward and outward.

SHOULDER

The shoulder joint is a synovial joint of the ball and socket variety. There is marked disproportion between the small shallow glenoid fossa and the large round head of the humerus. The shoulder is the most movable and possibly the least stable of all the joints of the extremities.

● Type: Scapula—fracture
Glenoid—rim fracture
Dislocation—subglenoid
Note: the humerus is addressed as a long bone in another section.

● Frequency: 13%. Acute dislocations are frequently associated with fractures of the bones of the shoulder girdle. This complication is found in approximately 25% of all dislocations; the greater tuberosity is most frequently involved (18-20%) (Depalma, 1970).

● Mechanism: Any alteration from the range of motion of the glenohumeral joint results in sprain, dislocation or fracture of the head of the humerus. The complete mobility of the upper arm is possible through action of the glenohumeral joint as well as articulation with the clavical and scapula. Impairment of any one reflects in impaired function of the shoulder, even though independent motion remains possible.

Fractures of the scapula are usually the result of a violent direct force.

Avulsion of portions of the glenoid rim can occur in acute dislocations of the joint. The fragment may detach anteriorly, posteriorly or inferiorly, determined by the type of dislocation reflected in the final resting place of the humeral head.

Inferior dislocation occurs when the arm is hyperabducted beyond the limits of the pivotal position. Inferior dislocation occurs if hyperabduction is continued after the arm has reached the pivotal position. The sequence of the mechanism is

Force
The arm is locked in the pivotal position and the scapula is completely rotated.

Force continues
The acromion, acting as a fulcrum, displaces the greater tuberosity and the inferior capsule is stretched.

Force continues
The head leaves the glenoid cavity and is displaced medially and inferiorly. The inferior capsule is torn. The rotator cuff is stretched and the arm drops. The head is in the subglenoid position.

● Etiology: Hyperabduction of the arm. Windblast forces exceed the physical limit of restraint. The forearm and hand (supine) are forced up and back, the elbow is fully extended as the scapula completely rotates and the hyperabduction mechanism is established. Associated glenoid rim fracture may be observed.

ELBOW

The elbow is a synovial joint formed by the articulation of the distal humerus and the proximal ulna and radius, forming a humero-ulnar and humero-radial articulation. The only appreciable movement possible at the elbow joint is the simple hinge movement of flexion and extension. This movement takes place in a line oblique to the humerus.

- Type: Fracture—interarticular
  Dislocation—posterior

- Frequency: 25%

- Mechanism: The general mechanism of injury is posterior displacement of both bones of the forearm. Severe concomitant soft tissue injury results. Because the radius and ulna are firmly bound by the annular ligament and interosseous membrane, a dislocation of one is usually primary to fracture or dislocation of the adjacent bone. Hyperextension of the joint disrupts the articulation, with subsequent posterior boney displacement.

Comminuted interarticular fracture is caused by trauma that drives the olecranon against the articular end of the humerus producing comminution of the distal end of the humerus. Flexion forces the ulna between the fragments of the distal end of the humerus.

- Etiology: Hyperextension of the joint results from severe arm loads forcing the forearm back and driving the elbow joint beyond the limit of its range of motion.

FEMUR

The thigh bone extends from the hip to the knee and is the longest and strongest bone in the body. Fractures of the femur are usually the result of severe violence. They may be transverse, oblique, greenstick, spiral or severely comminuted.

- Type: Fracture, mid-shaft

- Frequency: 9%

- Mechanism: Fracture of the femur is the result of traumatic impact, torsion or bending. Torque applied to the distal femoral shaft will induce stress at the mid-shaft. Intense local force application results in soft tissue injury at the injury sight.

- Etiology: Torque applied to the distal femoral shaft by rotation/abduction of the knee joint/calf/foot due to windblast.

- Severity: Usually, there is cardiovascular shock from the trauma to bone and soft tissue. Fracture of the shaft of the femur may be accompanied by marked concealed blood loss.

TIBIA—FIBULA

The tibia—fibula articulations are bound together by ligamentous fibers and interosseous membrane. The presence of a synovial joint at the upper end of the two bones indicates movement, but this movement is entirely passive. The tibia articulates with the femur above and the talus below. The fibula articulates above with the tibia and below with the tibia and talus.

- Type: Fracture—spiral
  comminuted
  plateau (knee joint surface)
  compound

● Frequency: 33%

● Mechanism: The lessions are produced by an angulatory or rotational force. Generally, angulatory forces produce transverse or short oblique fractures of both bones at the same level. Rotational forces produce transverse or short oblique fractures of both bones at the same level. Rotational forces produce spiral fractures at different levels (fibula fracture usually at a higher level than the tibial fracture). Fracture/dislocation of the ankle may be primary to fibula fracture.

● Etiology: Twisting of the foot/ankle secondary to external rotation-valgus movement of the foot/calf due to windblast. Blow to the fibular head due to dual leg garter configuration.

RADIUS AND ULNA

The radius carries the hand and is stabilized against the ulna for pronation-supination, and against the humerus for flexion extension of the forearm. The forearm injuries are marked in that impact with the aircraft structure generally provides the trauma inducing force.

● Type: Fracture—proximal
mid-shaft
compound
styloid process
coronoid process (ulna)

● Frequency: 10%

● Mechanism: A direct localized blow precipitates mid-shaft fracture. The type of injury sustained by the head or neck of the bone depends upon the intensity of the force applied and the position of rotation of the radius at the time of impact. The capitellum drives the radial bead outward, the direction of tilt depends on the rotational position of the radius.

● Etiology: Fuselage impact or pronating beyond anatomical limits resulting in posterior dislocation of the elbow by windblast induced hyperextension. After the break in continuity of the bones has occurred, the muscles controlling the different segments come into action and play a major role in the final position the fragments assume.

HUMERUS

Upper bone of the arm from the elbow to the shoulder joints, articulating with the ulna and radius and scapula. As such forces predisposing injury at these joints may involve the humerus.

● Type: Fracture—supracondylar
head
greater tuberosity
mid-shaft
transverse

● Frequency: 5%

● Mechanism: Most fractures of the shaft of the humerus are the result of direct violence. Involvement with shoulder and elbow injury is responsible for proximal fractures.

● Etiology: Direct violent blow to the long bone from fuselage impact. Force from windblast abduction/ dislocation of the shoulder or hyperextension of the elbow.

RANGE OF MOTION

Three sources of range of motion determination are presented for the major joints in Table 1. The magnitude of range is of interest because angular momentum (rotational velocity and its product with the appropriate anatomical mass) is a potentially high energy phenomenon occurring at the shoulder (and knee less dramatically) when the forearm/humerus are taken into rotary/posterior motion by windblast. The physiological dynamics of distributing and dissipating the energy of this motion are engaged when the limit of the hyperabducted joint is reached. Fracture is a major energy dissipation activity.

TABLE 1

NORMAL RANGE OF MOTION OF JOINTS IN MALE SUBJECTS

Comparison of Ranges of Motion (Degrees)			
Joint	*American Academy of Orthopedic Surgeons (Ref. 1)*	*Dempster (Ref. 2)*	*Barter et al., 1957 (Ref. 2)*
Shoulder			
Horizontal flexion	135	140.7 ± 5.9	134 ± 7
Horizontal extension	—	45.4 ± 6.2	48 ± 9
Forward flexion	158	166.7 ± 4.7	188 ± 12
Backward extension	53	62.3 ± 9.5	61 ± 14
Elbow			
Flexion	146	142.9 ± 5.6	142 ± 10
Extension	0	0.0 ± 3.1	—
Forearm			
Pronation	71	75.8 ± 5.1	77 ± 24
Supination	84	82.1 ± 3.8	113 ± 22
Wrist			
Flexion	73	76.4 ± 6.3	90 ± 12
Extension	71	74.9 ± 6.4	99 ± 13
Knee			
Flexion	134	142.5 ± 5.4	144 ± 9
Ankle			
Flexion (plantar)	48	56.2 ± 6.1	35 ± 7
Extension (dorsiflexion)	18	12.6 ± 4.4	38 ± 12
Forepart of the foot			
Inversion	33	36.8 ± 4.5	24 ± 9
Eversion	18	20.7 ± 5.0	23 ± 7

STRENGTH

Static capability of cancellous bone in compressive loading is presented in Table 2 as determined by seven investigators, and summarized in Combs, 1978, and Evans, 1957.

The dynamic environment of operational injuries was approached in Engin's (1979) measurement of resistive muscle force and moments (Table 3). Selected joints appear from that work.

TABLE 2

SOME PROPERTIES OF HUMAN, VERTEBRAL BODY, CANCELLOUS BONE (Ref. 3, 7)
(lower tharacic through lumbar)

Author	*Elastic modulus in compression MN/m^2*	*Ultimate compressive strength MN/m^2*	*Poisson's Ratio*
Galante, 1970		sup–inf. 2.0 a–p 0.8 lat. 0.7	
McEhalney, 1970	152	4.14	0.14
Rockoff, et al., 1920		2.1–15.8 intact body approx. 0.8–6.3 trabecular bone only	
Yamada, 1970 (Sonoda)*	70–90 compression (330 tension 1 specimen)	1.4–1.9 compression (3.7–4.0 tension)	
Lin, 1976	sup–inf 1117 a–p & lateral 558		0.36
Lindahl, 1976	1.1–139	1.0–7.0	
Kazarian, 1977	22.0–290.0	2.2–9.5	
Evans, 1973 (summary of 7 authors) Including McEhalney & Galante		1.4–8.0	

* Original Investigator

To allow operational comparison on the laboratory measured moment magnitudes, wind-tunnel pressure coefficient data were used to develop the values in Table 4. Following is the sequence used in deriving the force (N) value of column four in Table 4:

(1) A 1/32 scale F4E aircraft model was investigated in a 5 foot diameter, low-speed, wind-tunnel. The scale model pilot was affixed at the top of the catapult sequence, its feet level with the front canopy windshield, both totally enveloped in the flow. Static ports were drilled and manometer instrumented at selected anatomical locations. The pressure coefficients were measured.

(2) The recognized formula: $F = \frac{1}{2}\rho v^2 C_p S$ was used to calculate N/m^2 at the elbow, knee (side) and foot (toe) locations, for comparison.

(3) The anatomical area was estimated using mean value to determine elbow area, side of the knee area and frontal area of the foot. This allowed calculation of force (N) at that point.

(4) This value (Table 4, column 4) was then used with the moment arm, column 1, to calculate the magnitude of moment (N−m) of column 5.

(5) These data can be compared with Table 3 containing resistive moments to develop an appreciation for the severity of the windblast condition.

At 500 KTS, all the experienced moments are far beyond the resistive values given in Table 3. At a slower 300 KTS there is relative likeness. Remember, Table 3 data were collected with the participant anticipating the environment and focused on a single external force. The rapid establishment (1-2 seconds) of windblast loading could further reduce possible successful engagement of that environment.

TABLE 3

MAGNITUDES OF ACTIVE RESISTIVE MUSCLE FORCE AND MOMENTS (ENGIN: 1979)

Joint, Position	*Magnitude*	*Subject No. 1*	*Subject No. 2*	*Subject No. 3*
Shoulder				
Shoulder, lateral extension	Force (N)	140.01	144.91	138.61
		163.83	147.02	151.92
		198.14	160.32	177.83
	Moment (N-m)	49.38	55.15	56.29
		57.76	56.84	62.28
		68.93	62.29	69.48
Elbow				
Lower arm, 90° supination	Moment (N-m)	18.78	14.25	13.53
		22.05	14.97	14.77
		22.91	16.93	15.03
Lower arm, 90° pronation	Moment (N-m)	21.95	14.17	18.23
		26.16	17.18	22.81
		29.35	20.78	25.10
Knee				
Lower leg, rotated lateral limit	Moment (N-m)	36.92	23.07	43.63
		—	25.17	46.71
		—	32.24	49.59
Lower leg, rotated medial limit	Moment (N-m)	55.47	31.07	63.94
		—	35.65	93.14
		—	41.81	101.78
Ankle				
Tibial rotation, medial	Moment (N-m)	41.92	17.83	58.16
		47.11	23.40	65.04
		50.38	25.36	74.14
Tibial rotation, lateral	Moment (N-m)	30.11	20.99	52.61
		30.68	22.49	58.63
		32.04	24.52	61.78

TABLE 4

OPERATIONAL ENVIRONMENT MAGNITUDE OF MOMENTS

Joint	*Lever (m)*	*Airspeed (KTS)*	*Force (N)**	*Moment (N-m)**
Shoulder	0.504[1]	300	36	18.1
		500	103	52.0
Knee	0.453[2]	300	73	33.0
		500	220	110.0
Ankle	0.263[3]	300	130	34.3
		500	361	95.0

[1] mean, wrist to shoulder (Grunhofer: 1975)
[2] mean, bottom of foot to knee (ibid)
[3] mean, toe to ankle (ibid)

* (Nestle: 1979)
See level density of air used.

BIOMECHANICAL DATA

The biomechanical properties of long bones vary significantly with geometry, material properties, loading method, pathology, etc. Although there are numerous studies on the mechanical properties of bone in the literature, there are few that investigate intact long bone and joint failure precipitated by specific modes of disruption, resulting from experiences with force environments.

The majority of literature deals with the nature and physical properties of bone and, to some extent, static loading of intact bone. A broad summary of these efforts is given by Evans (1957) in his book entitled *Stress and Strains in Bone.* More recent surveys have been reported by Swanson (1971) and Kummer (1972).

So-called flail injuries, occurring as a result of large magnitude aerodynamic forces on the higher and lower extremities of the body, are represented by failure of the major articulating joints being forced beyond the anatomical limit of range and load of the structure as well as long bone trauma. Frequency of such injury had been documented by Combs (1978). Determination of voluntary range of motions, resistive force and movements and resistive torques for the rotational motion of the body segments about their long bone axis was accomplished by Engin (1979).

There is much that is still to be learned about long bone and joint response to mechanical loading. These injuries have significant operational impact and can be predisposing of long-term degenerative changes. Clinical investigations have been inadequate because there has been no way to assess the forces, their rate and direction of application in an actual injury. Present research programs are directed to simulate observable and explainable injury modes produced by windblast flailing, with bones and joints experiencing similar effects and constraints as those defined by the operational environment.

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